# Over Saturation Behaviour of SiPMs at High Photon Exposure

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**Abstract**

Several types of Silicon Photomultipliers were exposed to short pulsed (~ 30 ps) laser light with its intensity varying from single photon to well above the number of microcells of the device. We observed a significant deviation of the output of SiPMs from the expected behaviour although such response curve is considered to be rather trivial. We also noticed that the output exceeds the maximum pulse height, i.e. single photon pulse height times the total number of pixels. At the highest light intensity (~ 500 times the number of pixels) that we tested, the signal output reached up to twice the maximum pulse height, and still did not fully saturate.

*Keywords:* Semiconductor photo detector, Silicon Photomultiplier (SiPM), Multi Pixel Photon Counter (MPPC), dynamic range

## 1. Introduction

The Silicon Photomultiplier (SiPM) is a semiconductor photo detector which consists of multiple pixels (typically a few 100) of Avalanche Photodiodes working in Geiger-mode. Because of its characteristics such as compact size, low cost, insensitivity to magnetic fields, high photon detection efficiency (PDE) and high gain, the SiPM can be used in many different fields ranging from astrophysics, particle physics to medical imaging, as an alternative to vacuum Photomultiplier Tubes.

Due to its design, the SiPM dynamic range for simultaneously input photons should be limited to an order of the total number of pixels. This effect is reflected in a saturation behaviour of the SiPM response. The relation between the number of incident photons on the detector surface ($N_{photon}$) and the number of fired pixels ($N_{fired}$) can be described by the following model:

$$N_{fired} = N_{total} \times \left[1 - \exp\left(-\frac{N_{photon} \times \mathrm{PDE}}{N_{total}}\right)\right] \quad (1)$$

with $N_{total}$, the total number of pixels of the SiPM. Assuming a PDE of 50 %, equation 1 shows that the relation between the number of input photons and the output of an SiPM deviates from linearity by about 55 % at a photon intensity of $0.5 \times N_{total}$, 60 % at a photon intensity of $0.8 \times N_{total}$.

It is apparent also from equation 1 that the maximum output from the SiPM should be $N_{fired} = N_{total}$. However, we came across to observe an SiPM output exceeding this. We therefore measured the response curve, i.e. the relation between light input and output pulse height, for various SiPMs, all with 1 mm$^2$ sensitive area but different number of pixels and from different vendors. The models tested are the Hamamatsu MPPC S10362-11-100U (100 pixels, 100 $\mu$m$^2$ pixel size) and S10362-11-050U (400 pixels, 50 $\mu$m$^2$ pixel size), the SSPM-0611B1MM-TO18 from Photonique[1] with 556 pixels and a Zecotek MAPD-1 with 560 pixels. In addition, we performed a Monte Carlo simulation in order to obtain the response curve based on a geometrical consideration and the PDE. The result is shown in figure 1 together with the curve expected from the above model. The two curves are found essentially identical, indicating that the approximation of the SiPM response as in equation 1 is reasonable.

## 2. Setup and Method

To measure the response curve, the SiPMs were exposed to short light pulses with intensities ranging from single photons up to several ten thousand. The measurement setup is shown schematically in figure 2. All tests were done at room temperature (~ 25 °C). As light source we used a pulsed laser with 32 ps pulse width (FWHM) from Advanced Laser Diode Systems. The emission wavelength of the laser head (PIL040) is

[1]Photonique SA has suspended its operations. Product information can be found here: http://www.photonique.ch/LEGACY.

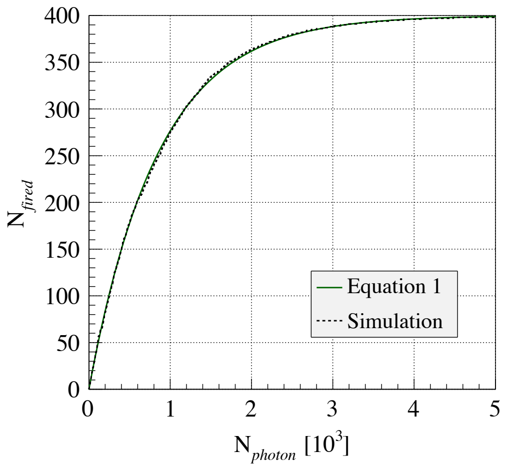


Figure 1: Comparison between simulated and modeled response of an SiPM with $N_{total}$ = 400. The PDE of 47 % was chosen as a typical value for the Hamamatsu S10362-11-050U at a wavelength of 400 nm.

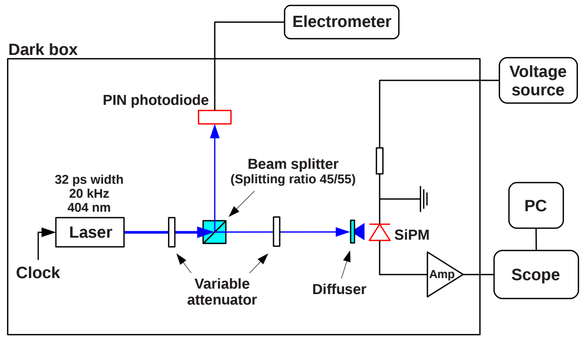


Figure 2: Schematic of the measurement setup.

$\lambda$ = 404 nm. The repetition frequency was set to the sufficiently low level of 20 kHz, considering the SiPM cell recovery time. After passing a variable optical attenuator, the laser pulses were split using a beam splitter with a splitting ratio of 45:55 (45 % reflectivity, 55 % transmission). One path of the beam is targeted at a Hamamatsu S5971 PIN photodiode for monitoring the light intensity. The current of the PIN photodiode was measured using a Keithly 6517 electrometer. After passing another variable optical attenuator, the second beam was directed to a diffuser in order to homogeneously distribute the light on the SiPM active area. The second attenuator in between beam splitter and SiPM is needed to deal with the different sensitivities of the SiPM and the photodiode. The SiPM signal was amplified by using a Photonique AMP-0611 preamplifier with a gain of about 23. The operation voltage of the sensor was typically set to $V_{over}$ ~ 1 V above the breakdown voltage. The SiPM response, i.e. the number of fired pixels, $N_{fired}$, was determined by measuring the output pulse height with the LeCroy WavePro 735Zi digital oscilloscope.

The PIN photodiode was calibrated by determining the relation between the number of incident photons and the photodiode output current, as illustrated in figure 3. We obtained this correlation at very low light intensities ($N_{fired}$ < 10, in case of Hamamatsu 100U, $N_{fired}$ < 20, for the others), where one can safely assume a linear behaviour of the response. In this calibration region, the number of incident photons on the sensor surface was calculated by $N_{photon} = N_{fired}/\text{PDE}$. Here we introduce the average number of "seeds", $N_{seed}$, which is the average number of photons arriving at the sensitive area of the SiPM, that could trigger an avalanche unless the cells are not saturated. The relation between $N_{seed}$ and $N_{photon}$ is given by $N_{photon} = N_{seed}/\text{PDE}$. This quantity will be used in the later discussion. The PDE values for the Hamamatsu MPPCs (72 % for 100U, 47 % for 050U at 400 nm) were taken from the data sheet. It's expected that these values are overestimating the PDE, since after-pulsing and cross-talk are included. These two effects would amount in ~ 20 % and ~ 10 % of the PDE [1], respectively. Since we are estimating $N_{fired}$ by measuring the signal pulse height and not the collected charge, we are not influenced by the effect of after-pulsing. For the Photonique SSPM and Zecotek MAPD, PDE values of 18 % and 30 % [2] for a wavelength of 400 nm were found. The uncertainty in the described calibration procedure resulted in a systematic error on $N_{photon}$.

## 3. Results

Figure 4 shows the measured response curves, $N_{fired}$ as a function of $N_{photon}$, for the Hamamatsu MPPC with 100 pixels and 400 pixels, as well as for the Photonique SSPM with 556 pixels and Zecotek MAPD with 560 pixels. In figure 4 the same data is presented always with wide range (left) and narrow range (right) of input photons. A spline curve is added to guide the trend of the response curve. The curve expected from the model as in equation 1 is also drawn in the figure for comparison. The expected outputs approach exponentially the maxima, $N_{total}$, which are indicated by the horizontal dotted lines. In case of the Hamamatsu SiPMs the data are plotted for two different values of the PDE and the model is calculated using a certain PDE range, since the values given in the data sheet are overestimating the PDE as described above.

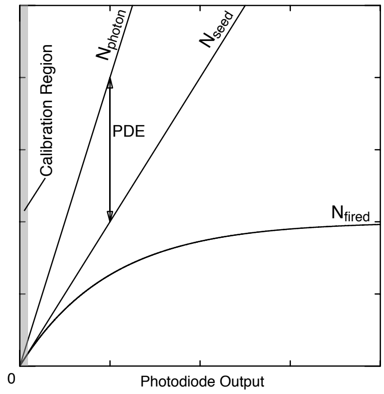


Figure 3: Schematic of the calibration method.

One notices, for all sensors we tested, that the data agree well with the expected response curve at the low photon intensity, however, it soon starts to diverge. It is clearly visible that the pulse height exceeds the maximum expected value. One notices also that the effect of this over saturation behaviour varies largely among the SiPMs tested here. The maximum output we obtained from Hamamatsu 050U (400 pixels) amounts roughly 800 p.e. equivalent, which would be the expected output for a sensor having twice the number of pixels. On the other hand, the Zecotek device with $N_{total} = 560$ seems less affected and the maximum measured output is $\sim$ 650 p.e. equivalent, that amounts $\sim$ 15 % larger output than expected. It is also to be noted that within the maximum light intensity ($\sim$ 200 k photons) we see no clear sign of full saturation of the device. Looking at the response curves of the MPPC with 400 pixels and the SSPM with 556 pixels, one can observe an additional enhancement of the dynamic range compared to the model calculation.

## 4. Discussion

For better comparison, the SiPM outputs ($N_{fired}$) are now normalized to the total number of pixels corresponding to the respective device. The data from all four SiPMs are overlaid and compared in figure 5. The plot shows clearly that the degree of the over saturation differs from one SiPM model to the other (figure 5 left). The largest effect is seen in Hamamatsu 050U, followed by Photonique, Hamamatsu 100U and Zecotek. The response curves are crossing (figure 5 right) because of the different PDEs of the photo sensors on the one hand and the varying strength of the over saturation effect on the other hand. At low number of induced photons, the SiPM response is still linear and the slope of the curve is mainly determined by the PDE. With increasing light intensity the data start to diverge from the expected behaviour (depending on the strength of the effect) and the curves cross.

In order to be free from the influence of the PDE when comparing different types of SiPMs, we plot $N_{fired}/N_{total}$ as a function of $N_{seed}/N_{total}$. Then the expectation curve appears as equation 2:

$$\frac{N_{fired}}{N_{total}} = 1 - \exp\left(-\frac{N_{seed}}{N_{total}}\right) \tag{2}$$

In this representation the response curve is now universal to all types of SiPMs. All data as well as the universal response function (equation 2) are overlaid and compared again in figure 6. We see here that the apparent crossings of curves present in figure 5 were dissolved as we anticipated. The Zecotek sensor appears to be the only device following the expected function at light inputs up to $N_{seed}/N_{total} = 4$ (figure 6 right).

In order to emphasize the degree of deviation from the theoretical function, we normalized figure 5 by the function given by equation 2. The results are shown in figure 7. At low light intensity ($N_{seed}/N_{total} < 0.3$), where actually the sensors are commonly used, the deviations are very small and all SiPM respond in a similar manner (figure 7 right). In this region it seems that the deviation from the theoretical function increases monotonically for all SiPMs. However, for higher light input we notice two qualitatively different tendencies of deviation. Around $N_{seed}/N_{total} \sim 0.5$ the deviation starts to decrease and tends to return to the expected value for Hamamatsu 100U and Zecotek sensors, before increasing again. For the other two SiPMs the deviation increases monotonically. Looking at the plot it becomes obvious that even the two Hamamatsu MPPCs, which are supposed to have a comparable response, show a different behaviour.

In a last step, we determined the over-voltage dependency of the SiPM response, as shown in figure 8 for the Hamamatsu 100U. At low light intensities ($N_{seed}/N_{total} < 0.3$) all curves are following the model given by equation 2 (figure 8 right). Increasing the light intensity the response curves deviate from the model calculation. Moreover, the deviation is strongly correlated with the applied over-voltage, especially for very high light intensities (figure 8 left).

Up to now, no explanation for this over saturation and enhanced dynamic range could be found. Other groups report a similar observation. In their case, however, the number of fired pixel is estimated using a charge ADC and as they mention the result could be explained

by the after-pulsing [3]. Moreover, such an effect can be understood there since the pulse width of the light pulses is comparable to or exceeds the pixel recovery time, as reported in [4]. In our case, we are free from an influence of after-pulsing as we evaluate the number of pixels from the signal pulse height and not from the collected charge. Furthermore, a pulse width (32 ps FWHM) much shorter than the recovery time was used.

To exclude effects from electronics, in particular a non-linear behaviour of the preamplifier at large input signals, the linearity of the preamplifier was confirmed in a measurement, which resulted in a mean gain of $23 \pm 0.8$. In addition, the over saturation behaviour was observed when the SiPM signal was not amplified but directly fed into the oscilloscope.

One explanation could be that a very high number of input photons per pixel may trigger several avalanches simultaneously, giving rise to a slightly higher output signal compared to the single photon signal. However, the fact that even the two MPPCs do not show the same behaviour is in contrast to this assumption and indicates a more complex effect behind.

In general one should notice, that SiPMs are typically not operated in the regime of very high light exposure since the output linearity is lost, but are preferably used to measure low amounts of light, in the linear, dynamic range, where measurement and model agree well. Therefore, most fields of application would not be affected by our observation. Nevertheless, understanding this behaviour would allow to use SiPMs for a wide range of light intensities, using calibration curves, of course with the drawback of decreasing accuracy for increasing intensity.

## 5. Conclusion

Our results show the SiPM signal response for a wide range of light intensity. For low light levels, the dynamic range of the photons follow the expected behaviour as given by the model equation. With increasing light intensities the signal response starts to diverge from the predicted values and exceeds the expected maximum by a factor between 1 and 2. Furthermore, at light intensities reaching 500 times the number of pixels still no saturation was observed. This behaviour was found for all tested devices, but varies in magnitude and seems not to be compatible with the fundamental understanding of SiPMs, that each pixel fires once whether only one or more photons have entered.


## Acknowledgements

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## References


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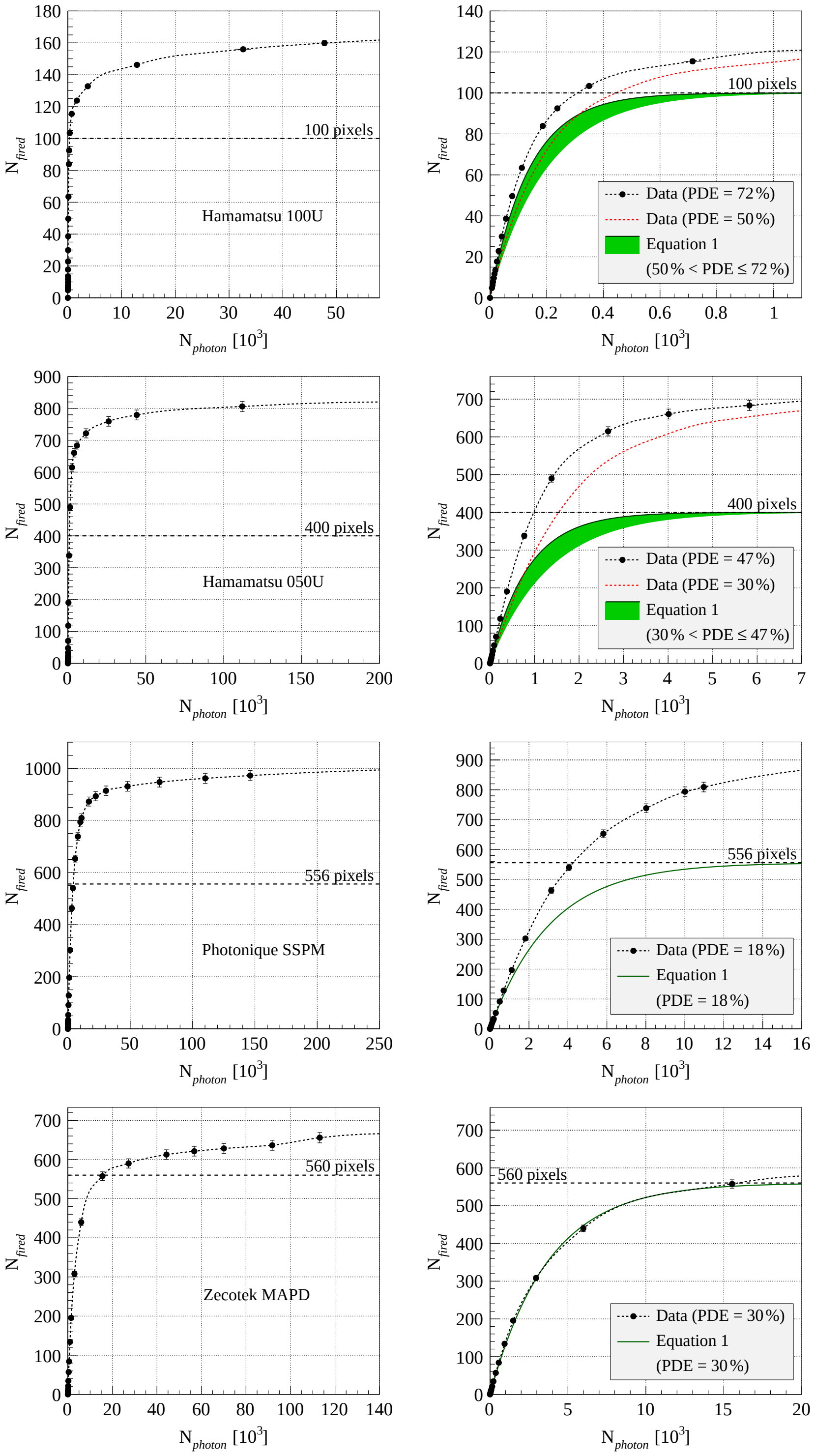


Figure 4: Response curves of Hamamatsu MPPC with 100 pixels operated at $V_{over}$ = 1 V, Hamamatsu MPPC with 400 pixels operated at $V_{over}$ = 1.2 V, Photonique SSPM with 556 pixels operated at $V_{over}$ = 1.2 V and Zecotek MAPD-1 with 560 pixels operated at $V_{over}$ = 0.7 V (top to bottom) for high light intensities (left) and low to medium light intensities (right). The data points are compared with the result of a model calculation given by equation 1. The expected values of saturation are indicated by the horizontal dashed lines.

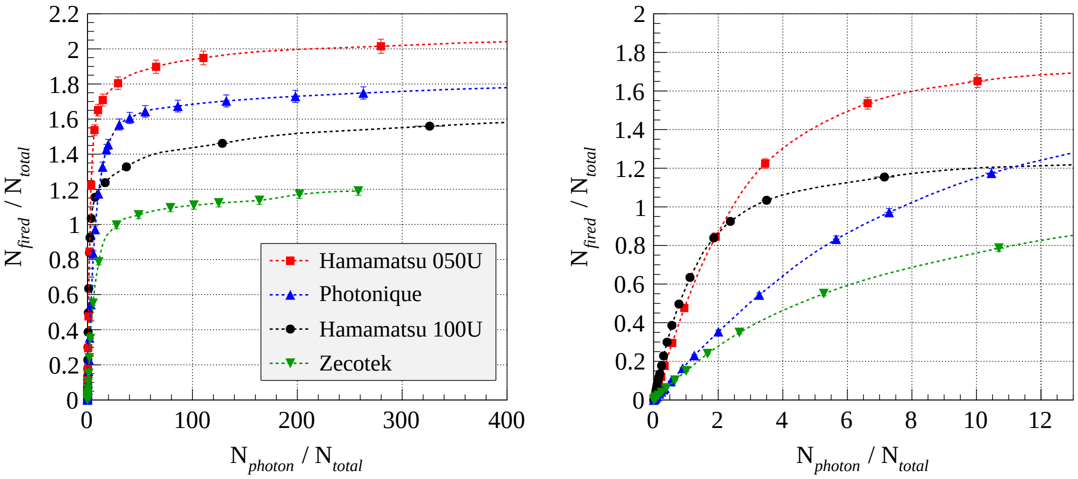


Figure 5: Response curves of various SiPM models, normalized to the total number of pixels of each device, $N_{total}$, for high (left) and low to medium light intensities (right).

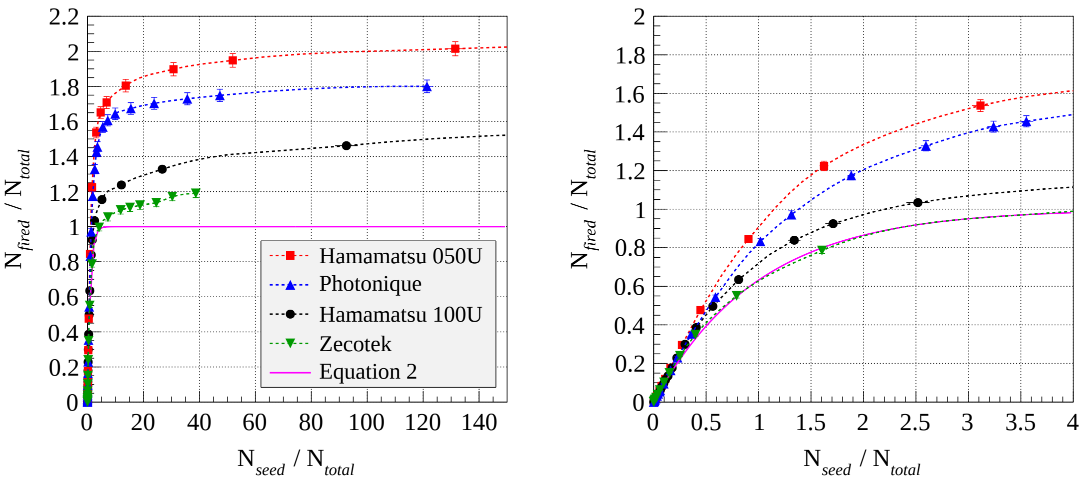


Figure 6: Response curves of various SiPM models, normalized to the total number of pixels of each device, $N_{total}$, for high (left) and low to medium light intensities (right). Additionally, the influence of the PDE is eliminated by plotting $N_{fired}/N_{total}$ as a function of $N_{seed}/N_{total}$.

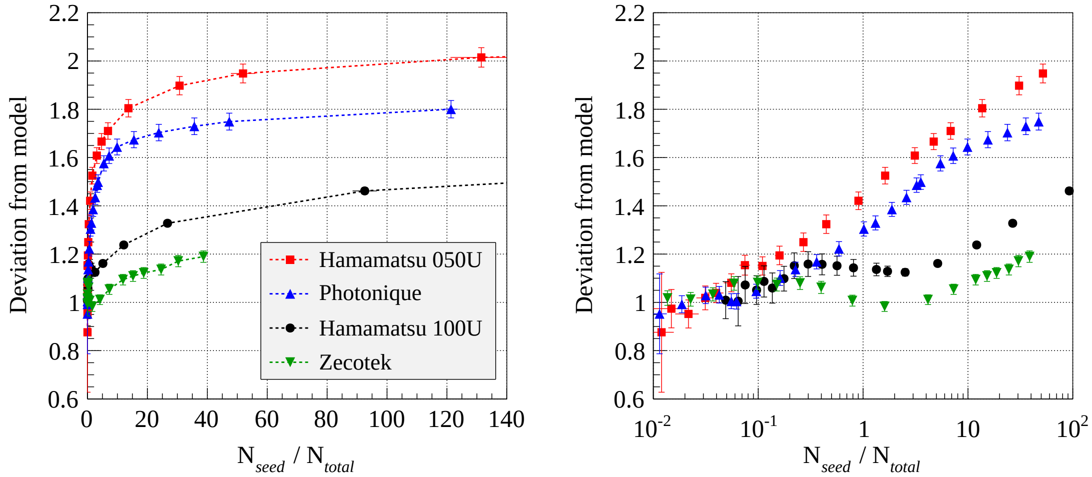


Figure 7: Deviation of the response curves of various SiPM models from the model curve given by equation 2. The results are normalized to the total number of pixels of each device, $N_{total}$. In addition, the influence of the PDE is eliminated by plotting $N_{fired}/N_{total}$ as a function of $N_{seed}/N_{total}$. The deviation is defined as the ratio between measured and calculated values.

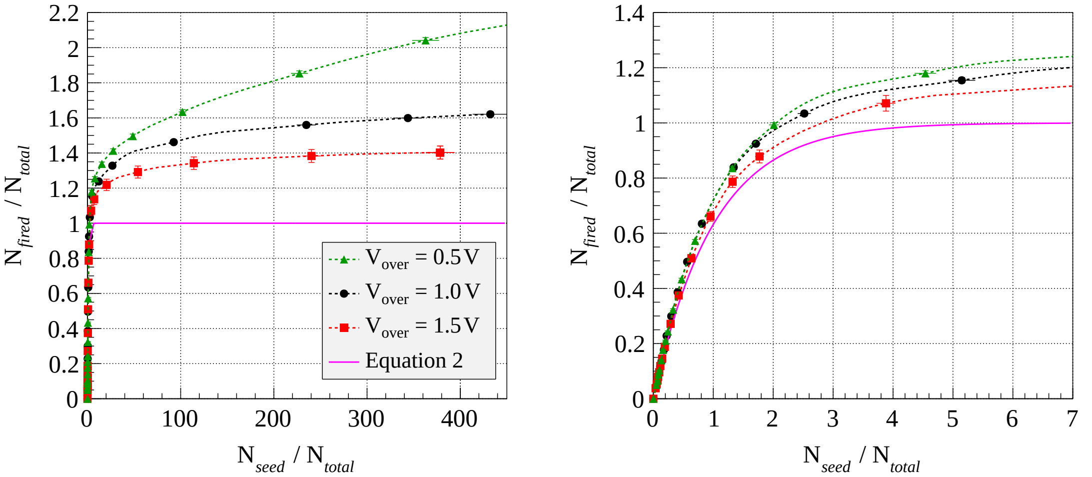


Figure 8: Over-voltage dependency of the response curve for Hamamatsu 100U. The data are compared with the model calculation given by equation 2. The results are normalized to the total number of pixels of the device, $N_{total}$. In addition, the influence of the PDE is eliminated by plotting $N_{fired}/N_{total}$ as a function of $N_{seed}/N_{total}$.